Three-Dimensional Laser Imaging System for Measuring Wound Geometry

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Background and Objective: **A low cost laser imager was designed and fabricated for measurement of wound geometry.** ***Methods:*** **The accuracy of the imager was validated using reference depressions of known dimensions. Perimeter, area, and volume were compared to planimetric and packing techniques on simulated wound models. Results: Wound tracing and alginate measurement methods required approximately 20 times longer for the reference standards, and 11 times longer for the simulated wounds than with the laser scanning method (LSM). LSM consistently overestimated the reference perimeter by 0.73 ± 0.20 cm and the area by 0.98 ± 0.62 cm^2. Volume estimates were not statistically different. The tracing method underestimated the perimeter by 0.34 ± 0.27 cm and the area by 1.07 ± 1.09 cm^2. Volume measurements by the alginate method were not statistically different. The perimeters of the simulated wounds averaged 1.29 ± 0.27 cm greater using the LSM than obtained by the tracing method, and areas greater by 2.02 ± 1.30 cm^2. Volume scans averaged 1.04 ± 0.61 cm^3 greater than by the alginate method. Lasers Surg. Med. 23:87–93, 1998.** **© 1998 Wiley-Liss, Inc.**

Key words: area; perimeter; wound care; volume

INTRODUCTION

By 1998, an estimated $2.5 billion will be spent annually in the United States on wound care and related products. During the first quarter of 1990, 30% of Skilled Nursing Facilities Medicare Part A moneys were expended on wound diagnoses at an annual cost of $52.6 million. The National Pressure Ulcer Advisory Panel notes that over $700 million was spent in 1988 on pressure relieving devices and local wound care products. This figure doubled by 1993 and is expected to show greater than a 3.5-fold increase by 1998 [1].

As the number of modalities to treat chronic wounds increase, the validity of these modalities must be tested. In the private practice setting, documentation of wound problems as well as progress of healing requires a rapid, highly reliable, low cost, accurate, reproducible method of assessment of wound dimensions. Stringent research and clinical assessments are vital to the success of proving the validity of new technological developments, as well as demonstrating the effectiveness of therapy provided in the clinical setting. The implications extend to standards of care and health care policy, and may extend to reimbursement for specifically effective therapeutic modalities [1,2].

Evaluation of healing is a dynamic process and requires an ongoing systematic, consistent analysis of both quantitative and qualitative data

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[3]. The commonly used objective measures of wound healing are based on planimetric, two-dimensional methods. Methods of measuring wound dimensions largely consist of direct measurements with a ruler [4], hand tracing of the perimeter of the wound with use of a grid to calculate wound area, or wound photography [5,6].

Although these methods are reasonable in cost, they are extremely time consuming and useful only in shallow wounds. Chronic wounds generally have a significant depth and heal from the base to surface rather than from the perimeter. Wound volume, therefore, is more indicative of the healing process. Methods for measuring wound volume include filling the wound with saline, dental molding compound, or alginate. Such time consuming techniques are cumbersome in clinical practice and impractical for large scale trials requiring precise wound measurements frequently repeated.

A noncontact laser wound imaging system could provide a quick, accurate method of measuring the perimeter, area, and volume of a wound. Such an instrument would require a minimum of space and technical expertise to utilize, and would have the advantage of low cost, portability, and ease of data transmission.

This study describes the development of a three-dimensional laser imaging system and validation of perimeter, area, and volume estimates in reference standards and wound simulations.

METHODS

Imager Principles

The imager is a structured lighting system that uses a laser line generator for illumination and two video cameras for image acquisition. The laser line generator produces a plane of light. A line is produced when the plane of laser light intersects the patient's body. Each video camera observes the line from an oblique angle [7]. Band-pass filters pass the wavelength of the laser but block out the ambient light allowing the imager to be used in normal illumination conditions. The position of the laser line in space is determined from the location of the line observed in the video image. A custom video capture card extracts the location of the laser line from the video signal. It is an ISA (Industry Standard Architecture) card that is used with an IBM (International Business Machines, Armonk, NY) compatible computer.

The laser and the cameras are mounted in a scanning head that moves on a linear track (Fig. 1). A cable extension encoder measures the position of the scan head on the track. The scan head is moved manually along the track in order to scan the wound. The scan head and linear track are mounted by a ball joint to a mobile stand. The ball joint allows the imaging system to be positioned at any arbitrary angle. A laptop computer used to operate the system is also attached to the stand. The laptop has an expansion bay for the ISA card.

A key component of the system is the custom ISA video capture board. The video capture board acquires video frames from each of the two video cameras, monitors the encoder position, then generates a hardware level interrupt. The video card also processes the image in real time. The position of the laser line is calculated for each video scan line. A threshholding process is used to determine the location of the laser line. For each camera, 10 bit values for the leading and trailing edge positions of the laser line on each scan line are placed in a buffer. When a video frame is complete a hardware interrupt is generated signaling the host computer to transfer the buffer. Video frames are captured at multiple locations along the linear track with each frame producing a profile of data for each camera.

The system is calibrated by presenting a set of known values to the imager. A calibration lookup table is used to convert scan line number and scan line position to x and y values. The z value is determined by the encoder position.

The scan sequence is initiated by the host software. The operator holds down a button to turn on the laser while moving the scan head along its track over the wound. The scan ends when the scan head is returned to the starting position. The data profiles are then displayed on the screen.

Software Principles

The host software is a Microsoft Windows (Microsoft Corporation, Redmond, WA) application using OpenGL for three-dimensional image display. As data is acquired from the imager board it is converted to x, y, z point data. This data is interpolated to a regular grid, usually at 1 mm x-y spacing. The interpolated data is displayed as a Gouraud shaded triangular mesh. The mesh can be rotated and zoomed. Figure 2 shows a wound scanned from a plaster model.

The wound perimeter, area, and volume are determined by an area of interest. The area of interest is created by selecting points around the edge of the wound on the display using the mouse

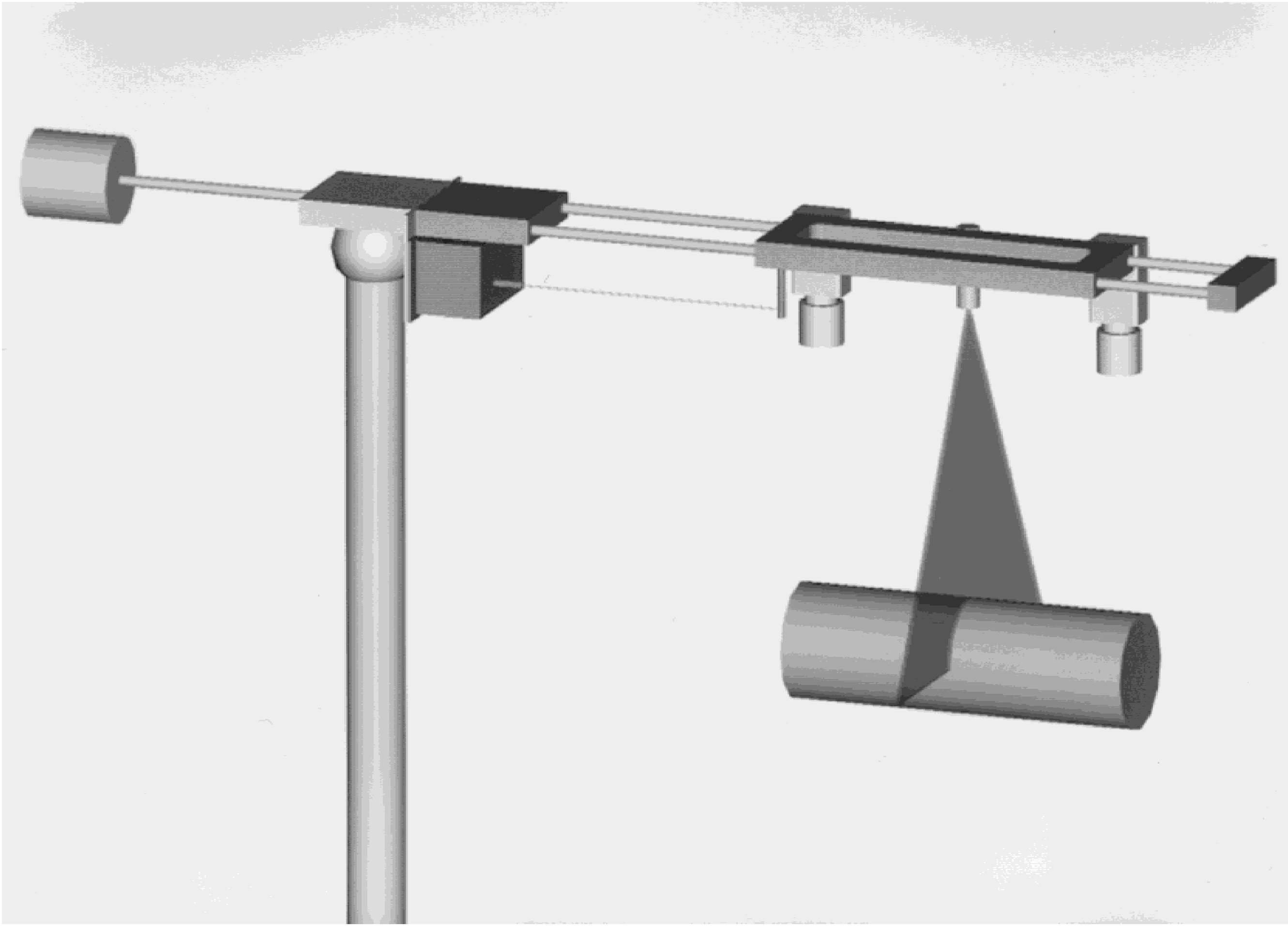

Fig. 1. CAD rendering of the laser imaging system.

cursor. A Catmull-Rom curve connecting the points is mapped to the surface. The perimeter is simply the length of the area of interest outline of the wound. A two-dimensional spline routine is used to build a surface over the wound. This surface approximates where the skin should be if there was not a wound. A triangular mesh is created to display the surface. The combined area of all of the triangles in the mesh is the surface area of the wound (Fig. 3). The volume of the wound is the volume between the spline surface and the surface of the wound inside the area of interest.

Experimental Validation

The accuracy of the imager was estimated by comparing the scanned perimeter, area, and volume values against a precisely known reference perimeter, area, and volume. Measurements were also made on simulated wounds carved into a plaster model of a lower leg and compared to measurements obtained using tracing and alginate methods [5,8–10].

The reference samples were a set of 6 hemispherical depressions in a block of plaster. The perimeter, area, and volume of the reference depressions were calculated based on micrometer measurements of their respective diameters, then measured with the imager and by conventional methods. The hemispheres used to prepare the depressions were 4.96, 3.75, and 1.74 cm in diameter respectively with two depressions for each diameter hemisphere.

Each of the 6 hemispherical depressions was measured 5 times with each technique. The conventional techniques of wound measurement that were used to measure the same test samples for comparison were wound edge tracing on transparent cellophane for perimeter and area [5] and alginate casting for determination of the volume [8–10]. Reference depression perimeter and area

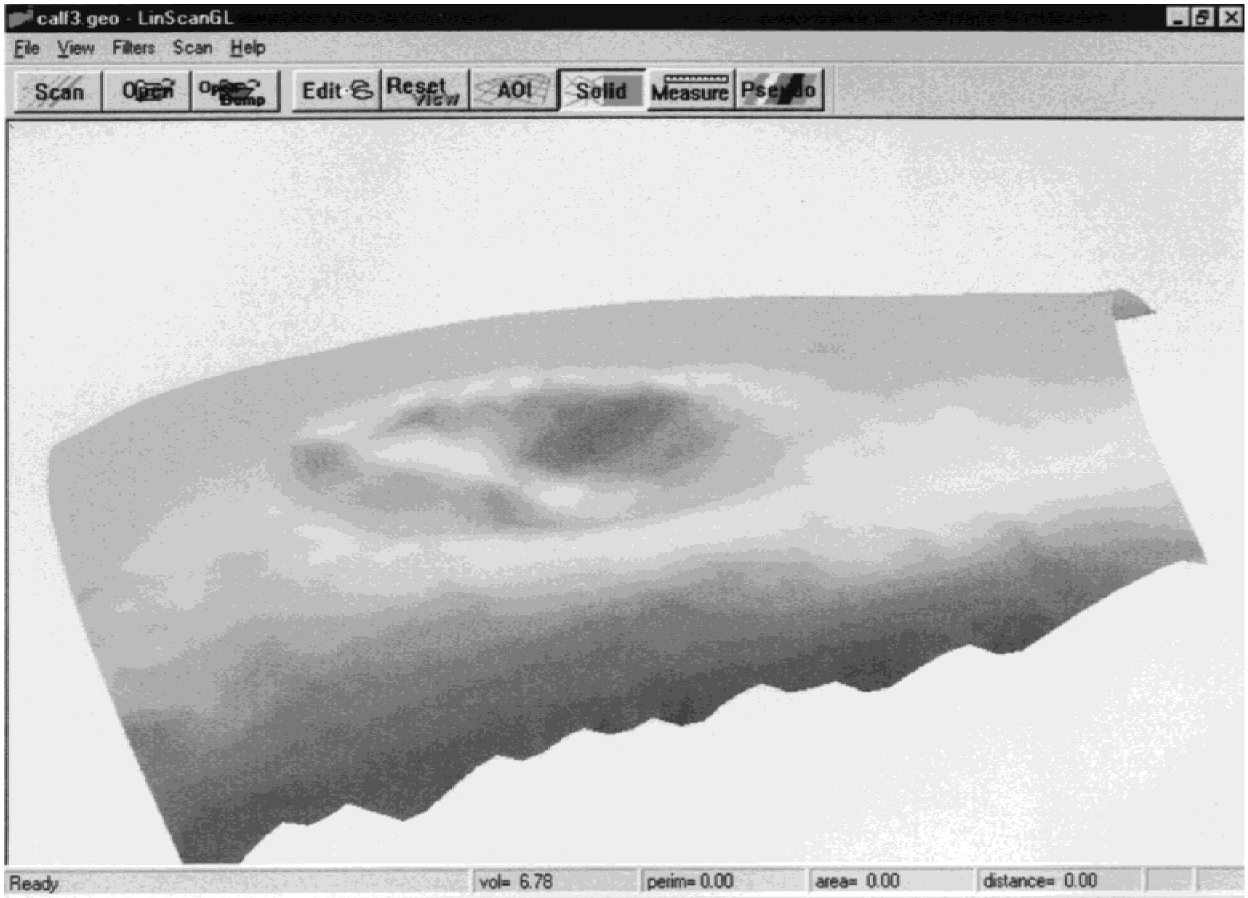

Fig. 2. Simulation of an ulceration on the calf carved into a plaster model of the lower leg.

were measured by planimetry directly from the cellophane tracings. The reference depressions were then filled with alginate, and after setting, excess alginate was trimmed so as to match the surface of the block. Volume was measured by submerging the alginate casts in water and noting the displacement.

Simulated wounds were also carved in a plaster model of the lower leg in the area of the shin, calf, and foot . Each simulated wound was measured 5 times by perimeter tracing and alginate techniques and 5 times by the imager. Data were analyzed by two-way ANOVA (Analysis of Variance) with $P < 0.05$ as the criterion for rejecting the null hypothesis.

RESULTS

The total time for making 30 measurements (6 depressions 5 times each) of the reference depressions using the laser imager was approximately 1.5 hours. The tracing and alginate techniques required approximately 30 hours for acquiring the same information. Table 1 presents the perimeter, area, and volume comparisons for the two measurement methods.

The imager data was more consistent than the data acquired by conventional means. There was a consistent statistically significant overestimation in both the perimeter and the area of the data acquired by the laser imager, 0.73 ± 0.20 cm and 0.98 ± 0.62 cm^2 respectively. Alternatively, the tracing method, on average, underestimated the perimeter by 0.34 ± 0.27 cm and the area by 1.07 ± 1.09 cm^2. Both measures were also statistically different from the reference values. Measured volume, however, was not significantly different than the reference standard for both techniques.

Measurement time for the simulated wounds (3 wounds, 5 times each) required 22.5 hours using the tracing/alginate methods and 2 hours using the laser scanning method (LSM). Estimates of the perimeters of the simulated wounds by the imager were on average 1.29 ± 0.27 cm greater than obtained by planimetry. Area was, likewise, greater with the LSM by 2.02 ± 1.30 cm^2. The

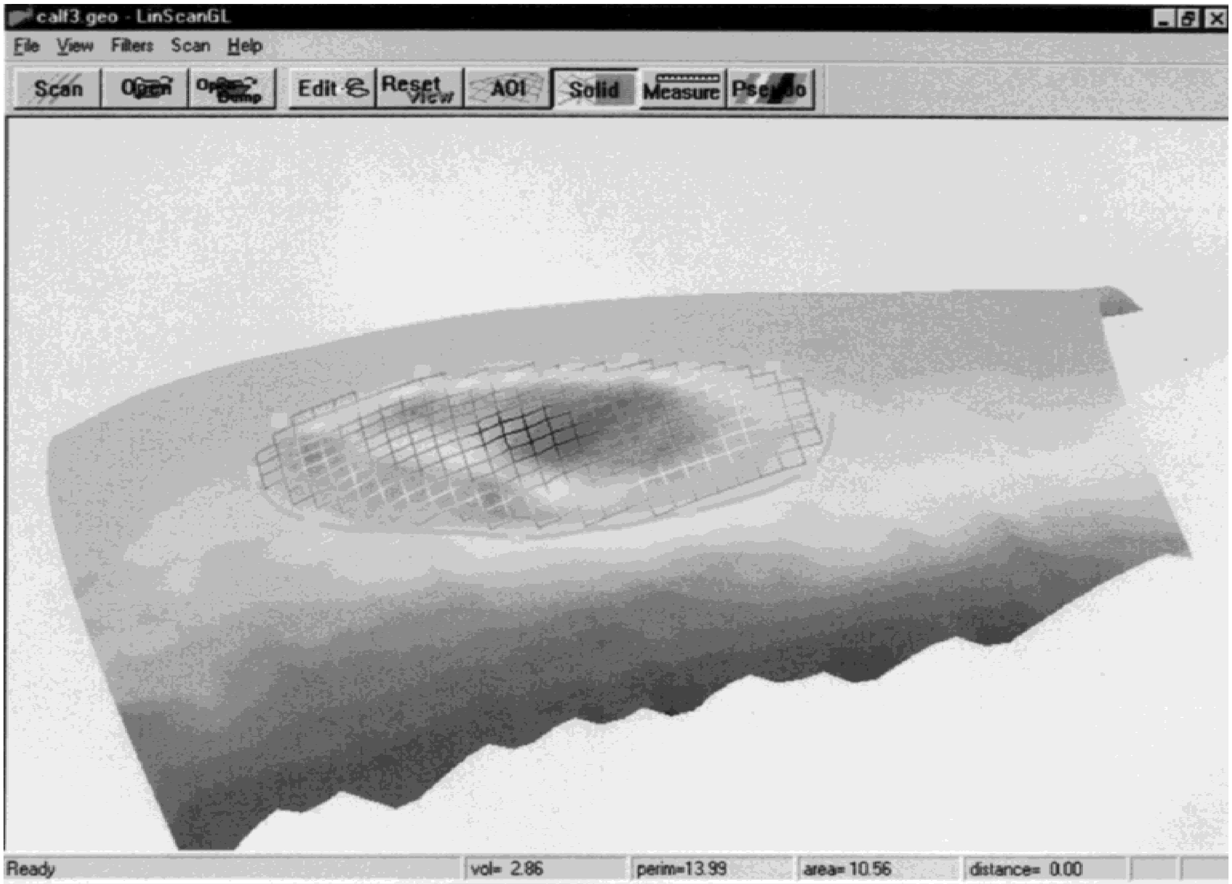

Fig. 3. Simulated shin ulceration with wire mesh interpolation of the skin surface.

wound volumes were 1.04 ± 0.61 cm^3 greater with the laser measurements compared to the alginate method. Differences between LSM and conventional methods for estimating perimeter, area, and volume were statistically different from one another (Table 2).

The cost of the system including a Pentium laptop computer was about $7,500 (Prostar Computer Inc., City of Industry, CA). This includes the expense of machining the parts but not the software development. The system cost could be lowered considerably by using less expensive cameras and an inexpensive encoder.

DISCUSSION

Evaluation of healing is a dynamic process and requires an ongoing systematic, consistent analysis of both quantitative and qualitative data [11]. The Wound Healing Society has stressed the importance and necessity of the development of a common system of language in describing wounds and in measuring their progress toward specific wound healing endpoints [12].

Accurate assessment of the extent of a wound requires a measurement of the perimeter, maximum dimensions of length and width, surface area, volume, amount of undermining, and determination of tissue viability [7]. There is a lack of clearly established standards for assessing and documenting wound progress [13]. This lack has been cited as a major obstacle to the assessment of effective wound management regimes [14].

The lack of established standards for assessing and documenting wound healing has been noted by several authors [13,15]. Commonly used objective measures of wound healing are based on planimeteric, two-dimensional methods. At present, measurement of wound dimensions largely consists of the following methods:

1. Direct measurements of length and width of the wound, with calculation of surface area [4].
2. Hand tracing of the perimeter of the wound with use of a grid to calculate wound area.

TABLE 1. Comparison of Conventional and Laser Scanning Method (LSM) Measurements to Reference Standards*

Perimeter (cm ± sd)	Reference	Tracing	LSM
1	15.58	15.52 ± 0.36	16.35 ± 0.02
2	15.71	15.32 ± 0.11	16.82 ± 0.16
3	11.78	11.70 ± 0.20	12.48 ± 0.05
4	11.78	11.56 ± 0.25	12.45 ± 0.11
5	5.84	5.24 ± 0.21	6.38 ± 0.07
6	5.84	5.14 ± 0.31	6.43 ± 0.03
Area (cm^2 ± sd)	Reference	Tracing	LSM
1	19.32	17.00 ± 0.76	20.93 ± 0.12
2	19.63	17.12 ± 0.54	21.38 ± 0.26
3	11.05	10.36 ± 0.16	12.03 ± 0.10
4	11.05	10.24 ± 0.38	11.95 ± 0.18
5	2.72	2.68 ± 0.17	3.00 ± 0.07
6	2.72	2.68 ± 0.10	3.07 ± 0.02
Volume (cm^3 ± sd)	Reference	Alginate	LSM
1	29.41	29.49 ± 1.25	29.31 ± 0.09
2	34.63	35.11 ± 0.70	34.62 ± 0.12
3	13.05	13.50 ± 0.28	13.10 ± 0.09
4	14.25	14.28 ± 0.10	13.74 ± 0.10
5	1.44	1.59 ± 0.06	1.41 ± 0.02
6	1.44	1.62 ± 0.72	1.42 ± 0.01

*Conventional and laser scanning method (LSM) measurements are statistically different from reference and from each other.

3. Use of a planimeter for perimeter tracing [5].
4. Wound photography with a surface grid to calculate surface area, and/or
5. Wound photography with subsequent computer image calculation of surface area or perimeter dimensions [6].

Although these methods are inexpensive to moderate in cost, they are useful only in shallow wounds. Chronic wounds typically have a significant depth. Healing takes place from the base to surface in chronic wounds rather than from the perimeter. Wound volume therefore becomes an important parameter to follow. Novel therapies in wound healing research as well as direct clinical management of chronic wounds require the development of a rigorous, readily acceptable, reliable tool capable of measuring wounds in three dimensions, with the ability to calculate perimeters, surface areas, and wound volumes. Unfortunately, wound depth and wound volume cannot be assessed adequately by direct measurement with a ruler because the surface is usually uneven, and may be covered by debris [16]. Methods for measuring wound volume include:

1. Saline technique [17]. The wound is covered with a transparent adhesive film, and injected with saline until it appears filled.
2. Dental mold technique [18].
3. Alginate cast technique [8–10].

Positioning of the patient can be problematic for use of the saline technique in certain circumstances. In addition, removal of the adhesive film required to perform the technique has been noted to be painful and unacceptable for some patients. The technique is not of use in large scale studies.

The dental mold technique has already given way to the cheaper and faster alginate cast technique. However, objections to its use have included the difficulty in accurately filling the wound, contact with the wound, and pain due to packing of the wound. The need to prevent the cast from drying out requires immediate measurement of the wound volume by suspending it in a water bath and measuring the amount of displaced water (Archimedes' principle) or by calculating the volume based upon the specific gravity of the material. Such time consuming techniques are cumbersome in clinical practice and impractical for large scale trials requiring precise, frequently repeated, wound measurements.

The three-dimensional laser scanning device described herein appears to provide consistent,

TABLE 2. Comparison Measurements of Perimeter, Area, and Volume Using Conventional and Laser Scanning Method (LSM)*

Perimeter (cm ± sd)	Tracing	LSM
foot	11.83 ± 0.52	12.90 ± 0.16
shin	15.00 ± 0.84	16.20 ± 0.26
calf	12.42 ± 0.20	14.00 ± 0.13
Area (cm^2 ± sd)	Tracing	LSM
foot	11.83 ± 0.90	12.44 ± 0.55
shin	14.41 ± 1.12	17.58 ± 0.72
calf	9.03 ± 0.50	11.32 ± 0.44
Volume (cm^3 ± sd)	Alginate	LSM
foot	1.04 ± 0.19	1.42 ± 0.10
shin	1.49 ± 0.19	2.64 ± 0.09
calf	1.17 ± 0.05	2.76 ± 0.05

*Conventional and laser scanning method (LSM) measurements are statistically different.

reliable measurements of perimeter, area, and volume. Most importantly, this approach avoids contact with the wound thus minimizing patient discomfort and the potential for infection. The ease and speed with which measurements can be made and relatively low cost allows regular assessment of wound healing in relation to therapy, as well as produces a hard copy for later reference.

The consistent overestimation of perimeter and area by the three-dimensional laser scanner is judged to be primarily an error in marking the margins of the reference depressions. Since the wound margins are marked by hand after the scan is rendered on the screen, errors in placing the margin definitions may account for a portion of the overestimation. Additionally, the analysis software is set to interpolate to a 1 mm grid. The sharp edge of the depression is rounded off to the nearest mm radius, on the average, resulting in approximately a 4 mm error in the diameter. This error is expected to be significantly lessened after automatic edge detection and smaller grid interpolation is incorporated into the analysis software. However, the consistency of measurement is of greater importance. Whereas the volume estimates of the reference standards correlated highly between both methods, mock wound volumes differed fairly significantly. The source of the difference may be due to the artistic nature of the alginate gel method. The alginate is packed into the wound then matched to the skin surface by sculpting, whereas the technique used by the imager tries to match the opposite edges of the wound with a spline curve. Additionally, the imager appears to be less subject to differences between operators, and the speed and simplicity of the imager's operation makes it suitable for extensive clinical studies of wound healing where repetitive measurements are required.

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